Collectivity in intermediate-scale QGP and extended hydro. regime

Hydro. *Extended Hydro. Regime*

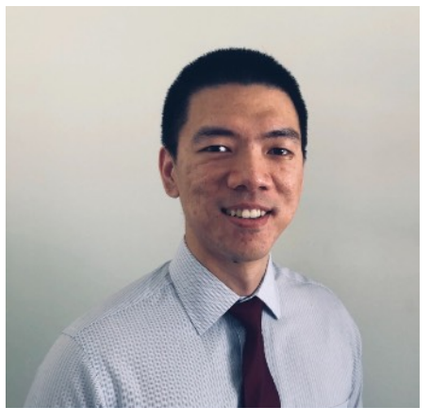
(characterized by $\eta, c_s^2, \ldots$*)* *(characterized by* $\eta', \tau'_\pi \ldots$*)*

Institute of Modern Physics (IMP), Lanzhou, Chinese academy of sciences

Yi Yin

Weiyao Ke and YY, 2022.04XXXX

QM22, Apr. 7th, 2022



Weiyao Ke @ LANL

QGP properties vs scale/gradient

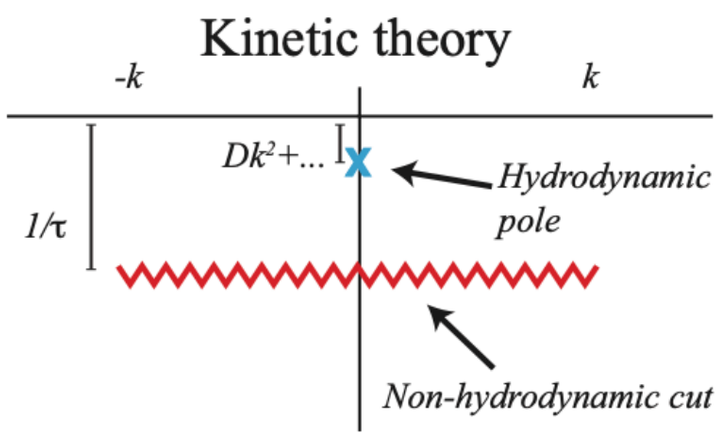
- Unexplored regime: QGP at mesoscopic scale where typical gradient k is too large for vHydro. and too short for pQCD.

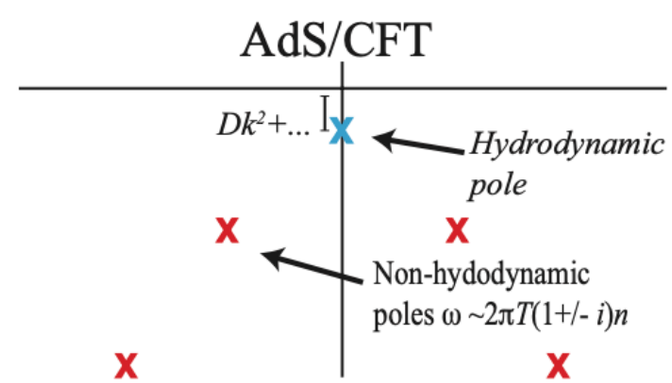
- Exploring QGP mesoscopy:
  - Large angle scattering between jet and the medium.
  - Collectivity in small systems.
  - This talk: medium response (how response changes with varying gradient).

e.g. Eramo, Rajagopal and YY, JHEP 19; Hulcher's talk Tues.

works by Kurkela, Mazeliauskas, Wiedemann, Bin Wu, ….

Medium response and excitations





The analytic structure of retarded Green function

Fig. from Kurkela-Wiedemann-Wu, EPJC 19'

- The (linear) response of a thermal system to an in-homogeneous disturbance is determined by excitations.

$$O(t, \vec{k}) = A_H e^{-i\Omega_H(k)t} e^{-\Gamma_H(k)t} + \text{other excitations}$$

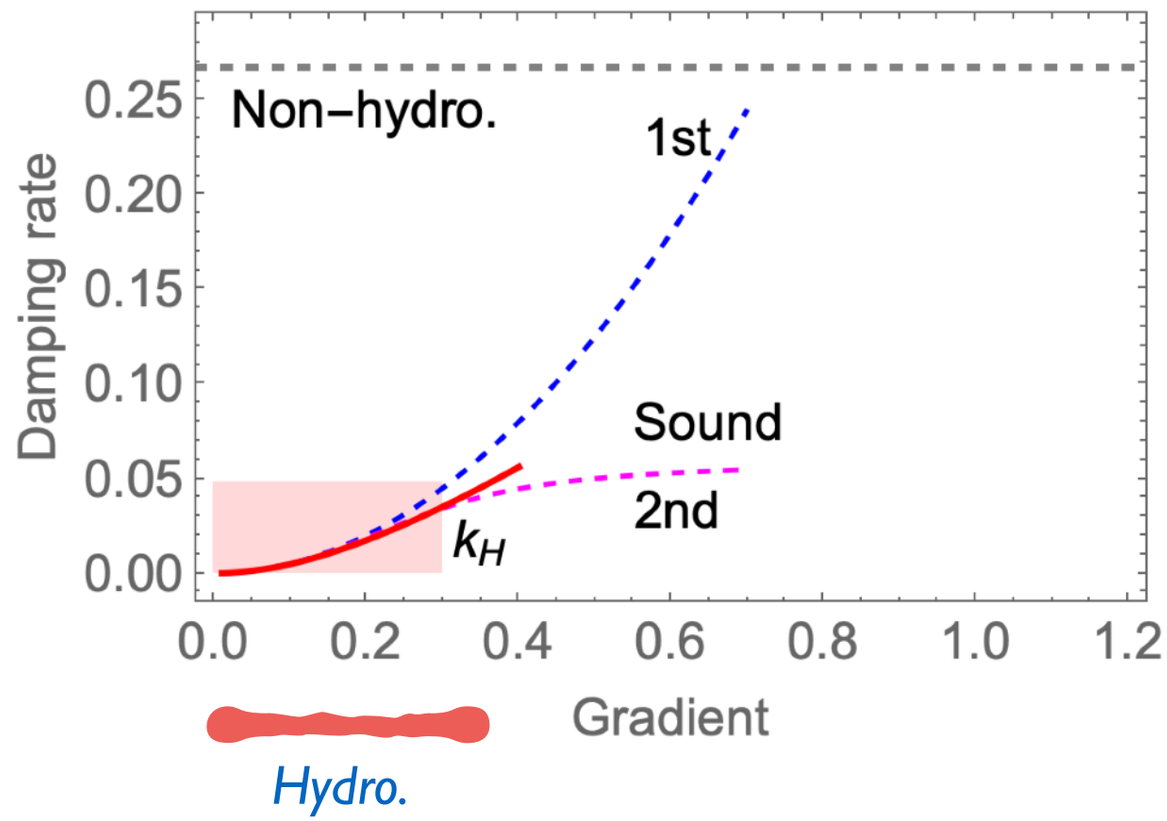
hydro. modes

- In general, describing response is complicated as it involves various excitations.

- Simplification?

Hydro. regime

Relaxation time approximation (RTA) kinetic equation



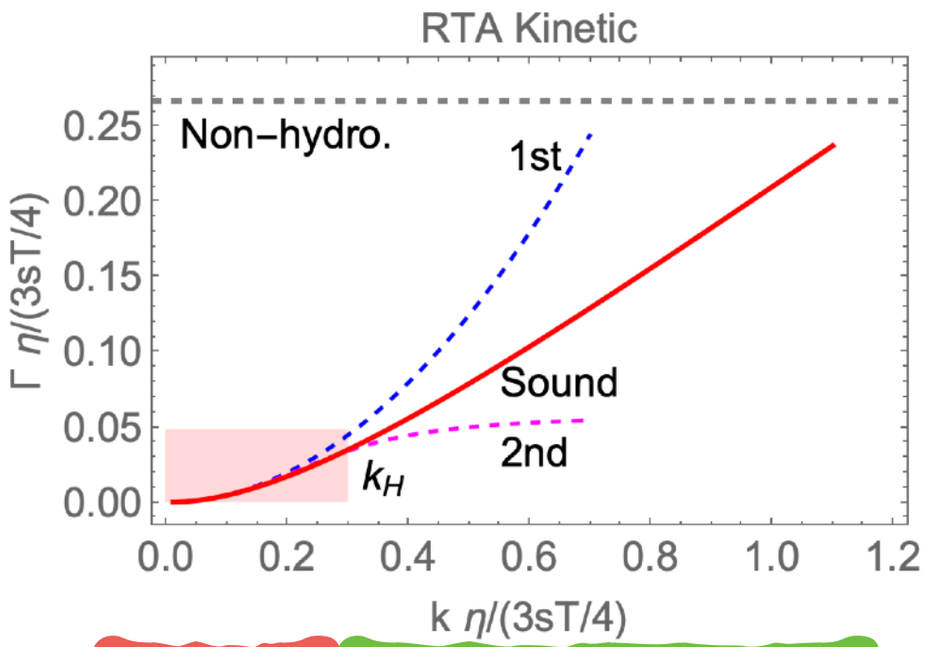
- At small k, hydro. modes are gapped (smaller damping rate) from non-hydro excitations and hence dominate the response.

- Hydro. regime: $k < k_H$ where viscous hydro. works.

What happens when $k > k_H$?

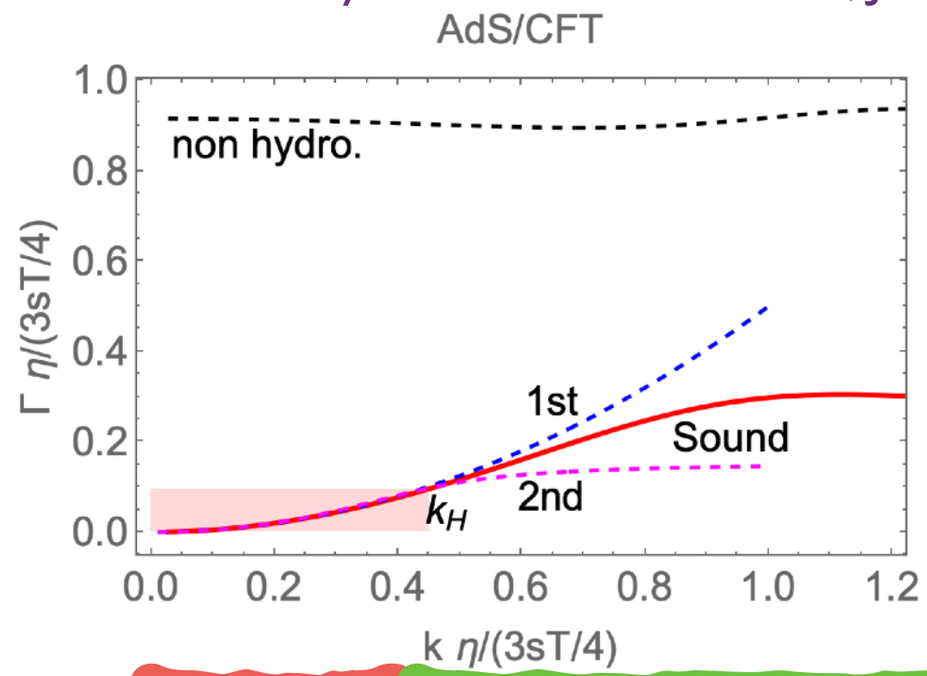
The generality of extended hydro. regime (EHR)

Romatschke, EPJC 16'.



Hydro. *EHR in kinetic theory*

Amado-Hoyos-Landsteiner-Montero, JHEP 08



Hydro. *EHR in AdS/CFT*

- Extended hydro. regime (EHR):
  - sound mode is gapped => "sound dominance";
  - dispersion is different from vHydro.

See our upcoming paper for the discussion of shear channel.

- The presence of EHR seems generic; may be relevant for QGP.

The implication of EHR (if exists)

- The collectivity persists at intermediate gradient.
- Description of medium's mesoscopy might be simplified.

NB: the notion of EHR bears a certain similarity to the far-from-equilibrium hydro. for expanding QGP. The main difference is that EHR describes perturbation around a bulk profile but not the bulk evolution itself.

Towards describing EHR

- Adding higher gradient terms (the radius of convergence; proliferation of inputs).

Grozdanov-Kovtun-Starients-Tadic, PRL 19', JHEP 19;

Heller-Serantes-Spalinski-Svensson-Withers, PRD 21'.

- An alternative: constructing a simple model with a few parameters such that

  - it reduces to hydro. in small k;

  - describes sound mode in (at least part of) EHR.

MIS* (a simple yet non-trivial extension of Mueller-Israel-Stewart (MIS) eqns) serves the purpose.

partly inspired by Hydro+, Stephanov-YY PRD 18'

MIS*: deforming MIS equation

- Consider the decomposition: $T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + \pi^{\mu\nu}$
- MIS Eqns

$$D\pi^{\mu\nu} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} + \eta\partial^{<\mu}u^{\nu>}\right) - \ldots$$

shear strength

- MIS* (for a conformal system):

$$\pi^{\mu\nu} = -\eta'\partial^{<\mu}u^{\nu>} + \widetilde{\pi}^{\mu\nu}$$

dynamical

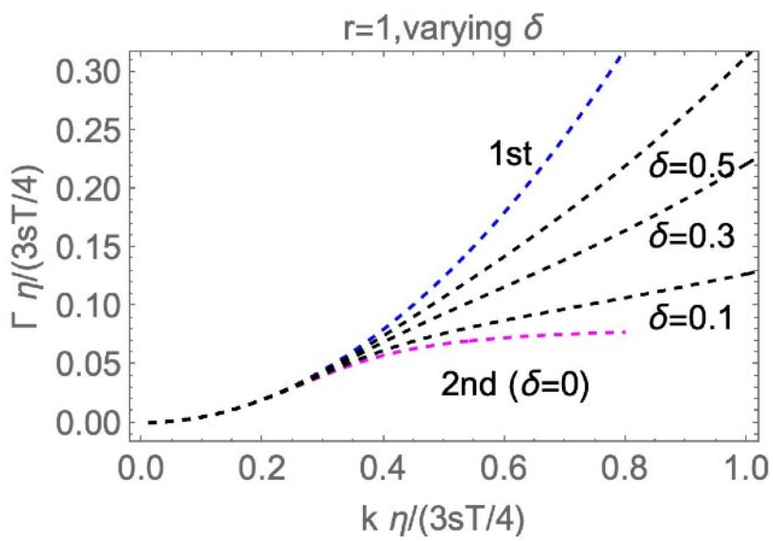
$$D\widetilde{\pi}^{\mu\nu} = -\frac{1}{\tau'_\pi}\left(\widetilde{\pi}^{\mu\nu} + (\eta - \eta')\partial^{<\mu}u^{\nu>}\right) - \ldots$$

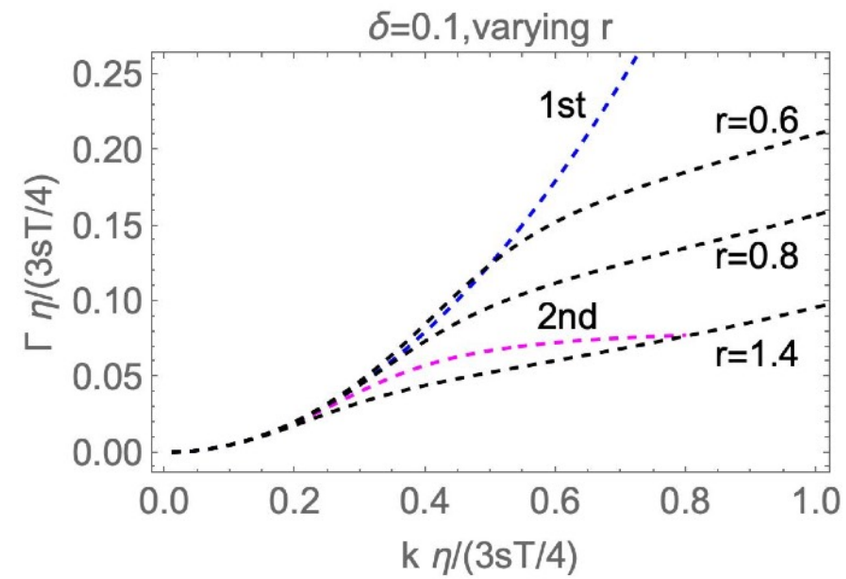
- MIS* parameters: $\eta' \sim$ the effective viscosity in EHR and τ'_π controls the boundary separating hydro. and EHR.

$$\delta = \frac{\eta'}{\eta} \qquad r = \frac{\tau'_\pi}{\tau_\pi}$$

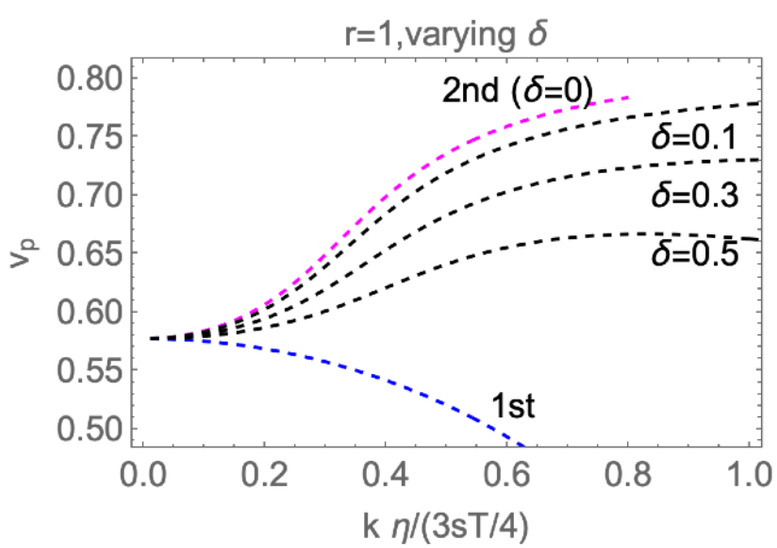
When $\delta = 0$,
$r = 0$ *(1st order hydro.);*
$r = 1$ *(2nd order hydro).*

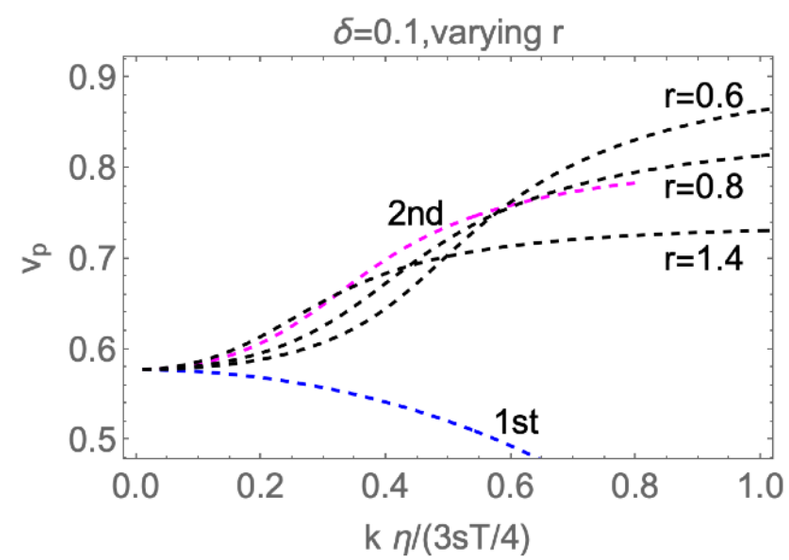
Flexibility/capability of MIS*





- Increasing δ=η'/η increases damping rate.
- Changing $r = \tau'_\pi/\tau_\pi$ varies boundary between hydro. and EHR.

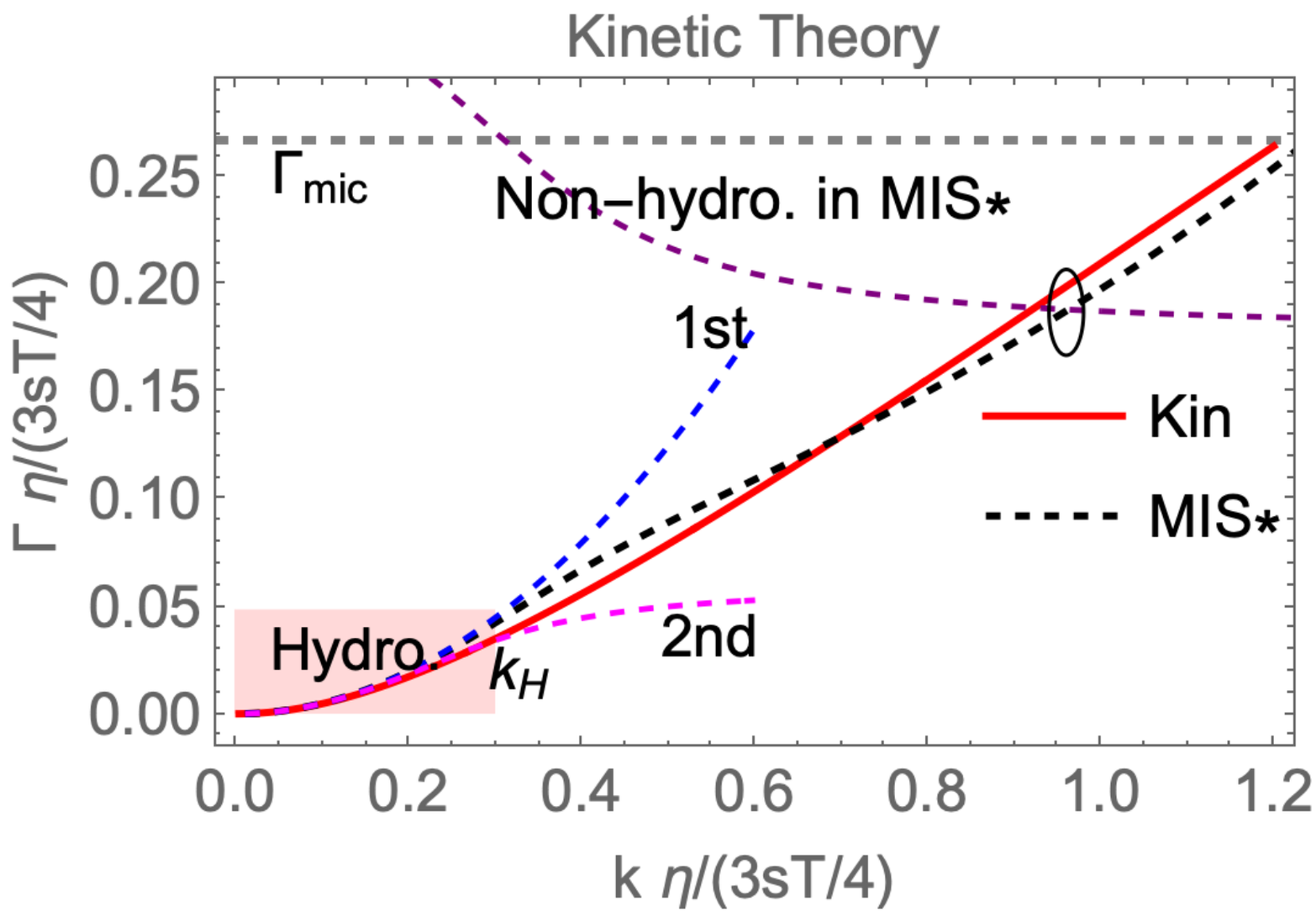




- (r,δ) in combination controls sound propagation in EHR.

MIS* vs kinetic theory

$(\delta, r) = (0.25, 0.8)$

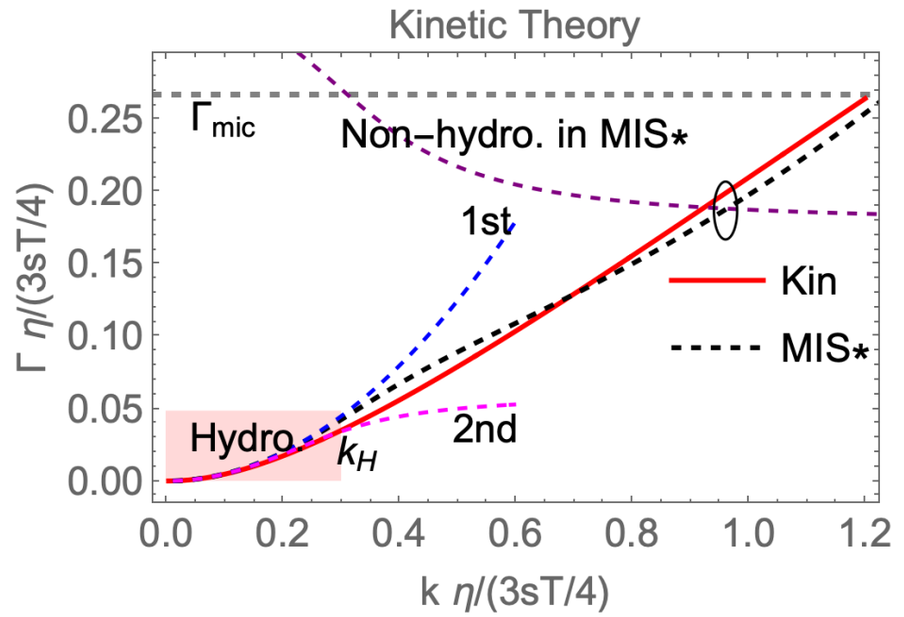


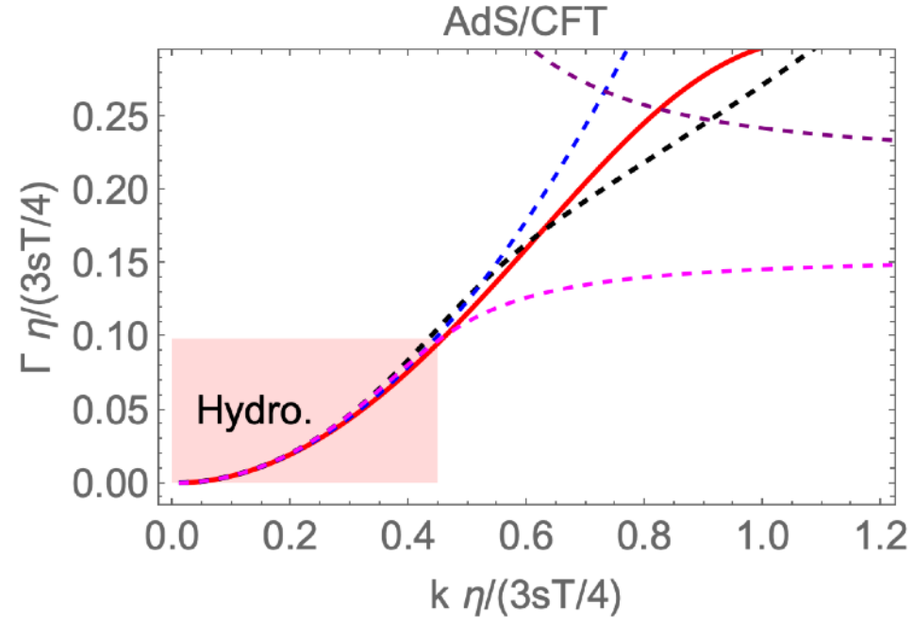
*EHR in MIS**

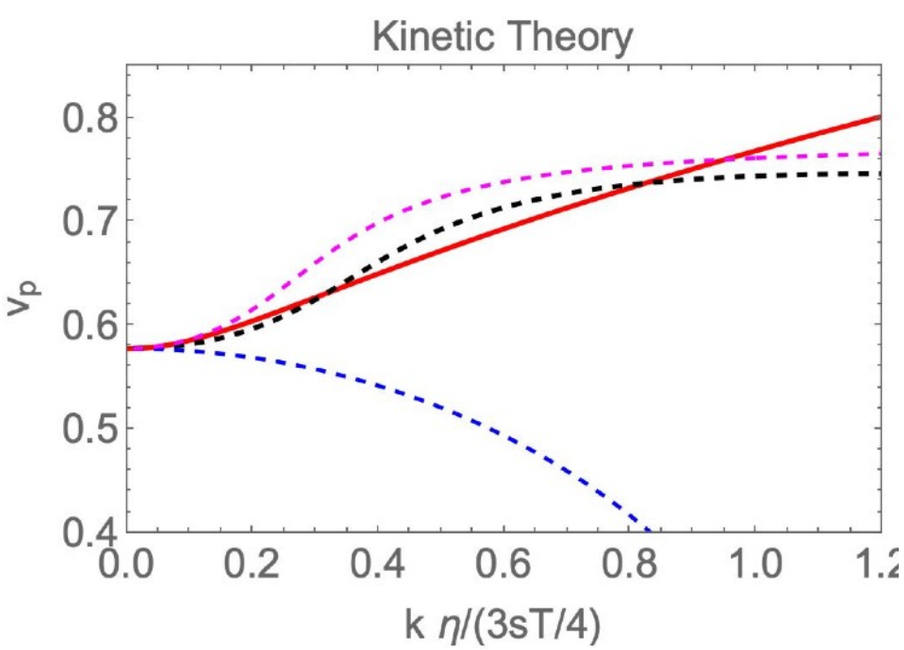
Hydro. *EHR in kinetic theory*

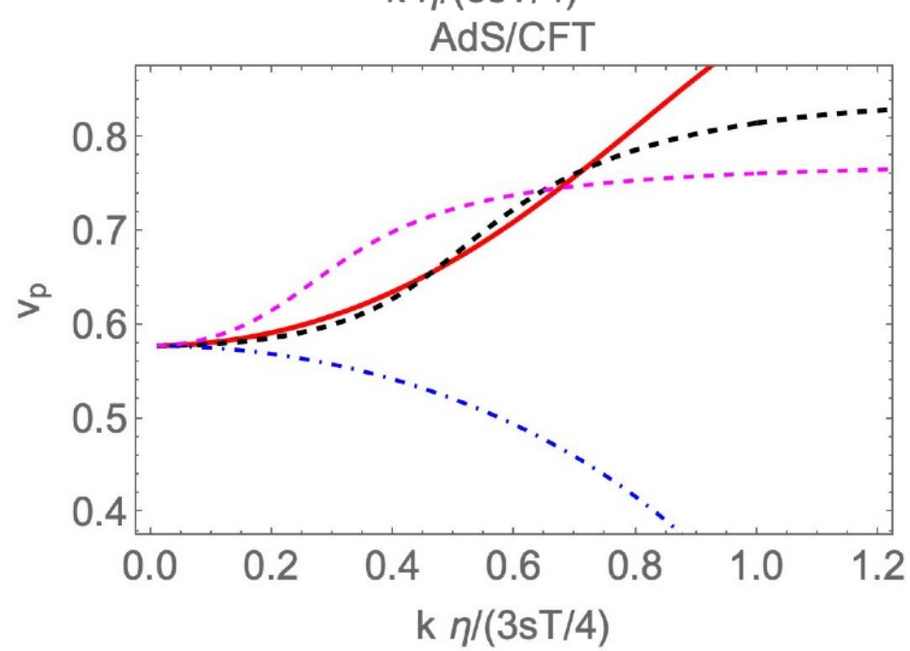
MIS* describes both kinetic and AdS/CFT theory in EHR

RTA Kinetic.: $(\delta, r) = (0.25, 0.8)$ AdS/CFT: $(\delta, r) = (0.25, 0.95)$









Hydro. *EHR in MIS**

Hydro. *EHR in MIS**

Extended hydro. response for Bjorken expanding plasma

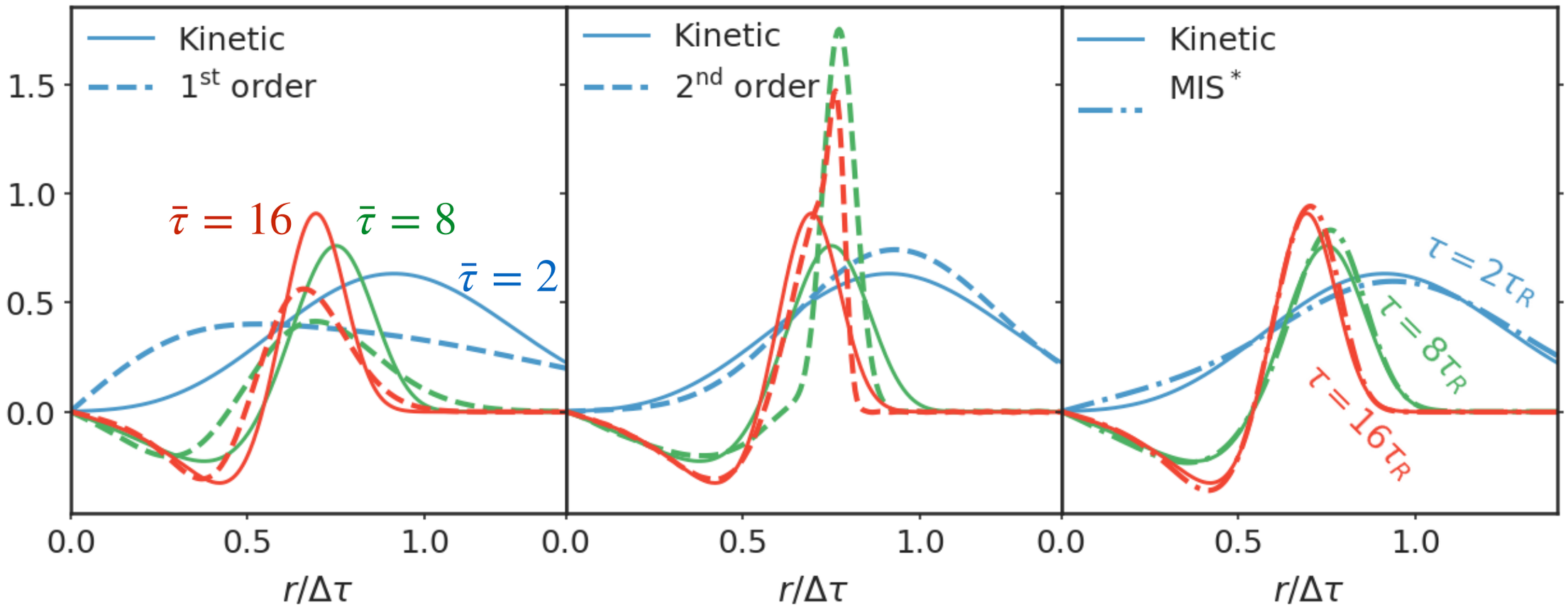
- Motivation:
  - complementing the study of a static medium;
  - exploring the prospects of detecting EHR through jet-medium interaction.
- Consider e.g. energy-energy response function.

c.f. KOMPOST et al

$$\delta\epsilon(\tau, x) = \int_{\tau_I}^{\tau} d\tau' \int_{x'} \underbrace{G_{\epsilon\epsilon}(\tau, \tau'; x - x')}_{\text{response function}} \underbrace{S_\epsilon(\tau', x')}_{\text{Source}} + \ldots$$

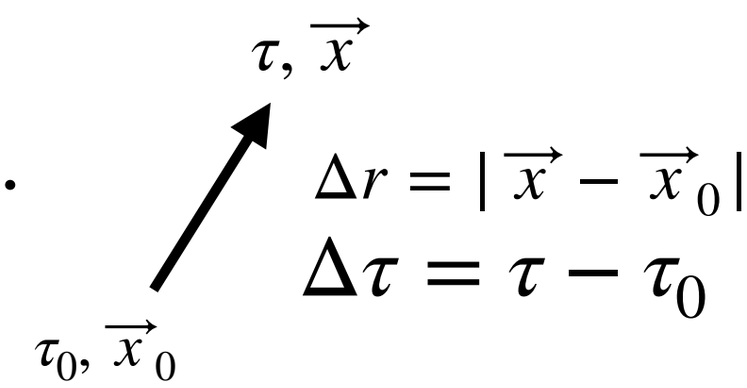
RTA kinetic vs MIS*

$\bar{\tau} = \tau/\tau_R, \qquad (\delta, r) = (0.15, 0.7)$



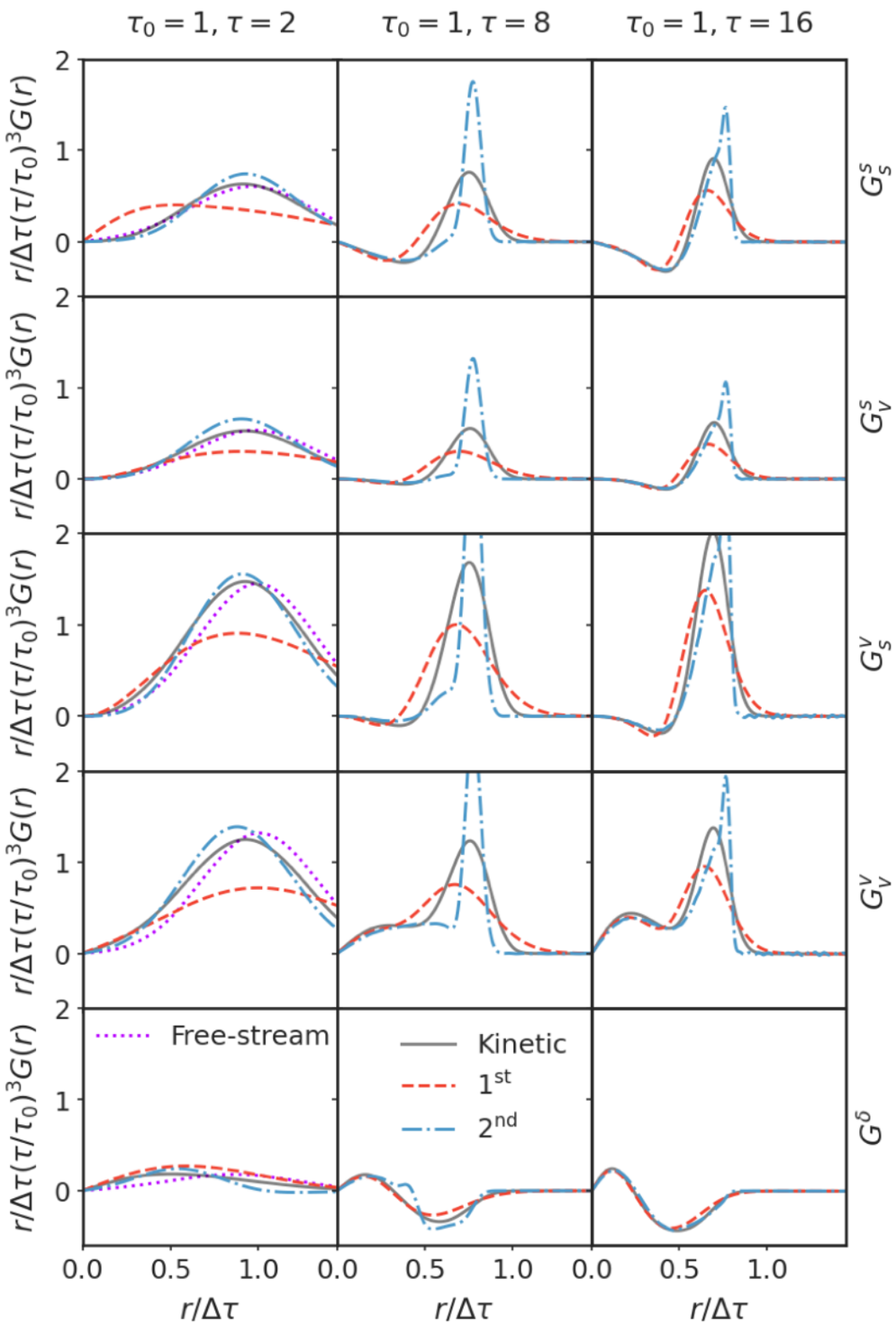
Energy-energy response function. The disturbance is sourced at $\tau_0 = \tau_R$ (equilibrated plasma).

- MIS* describes extended hydro. response.

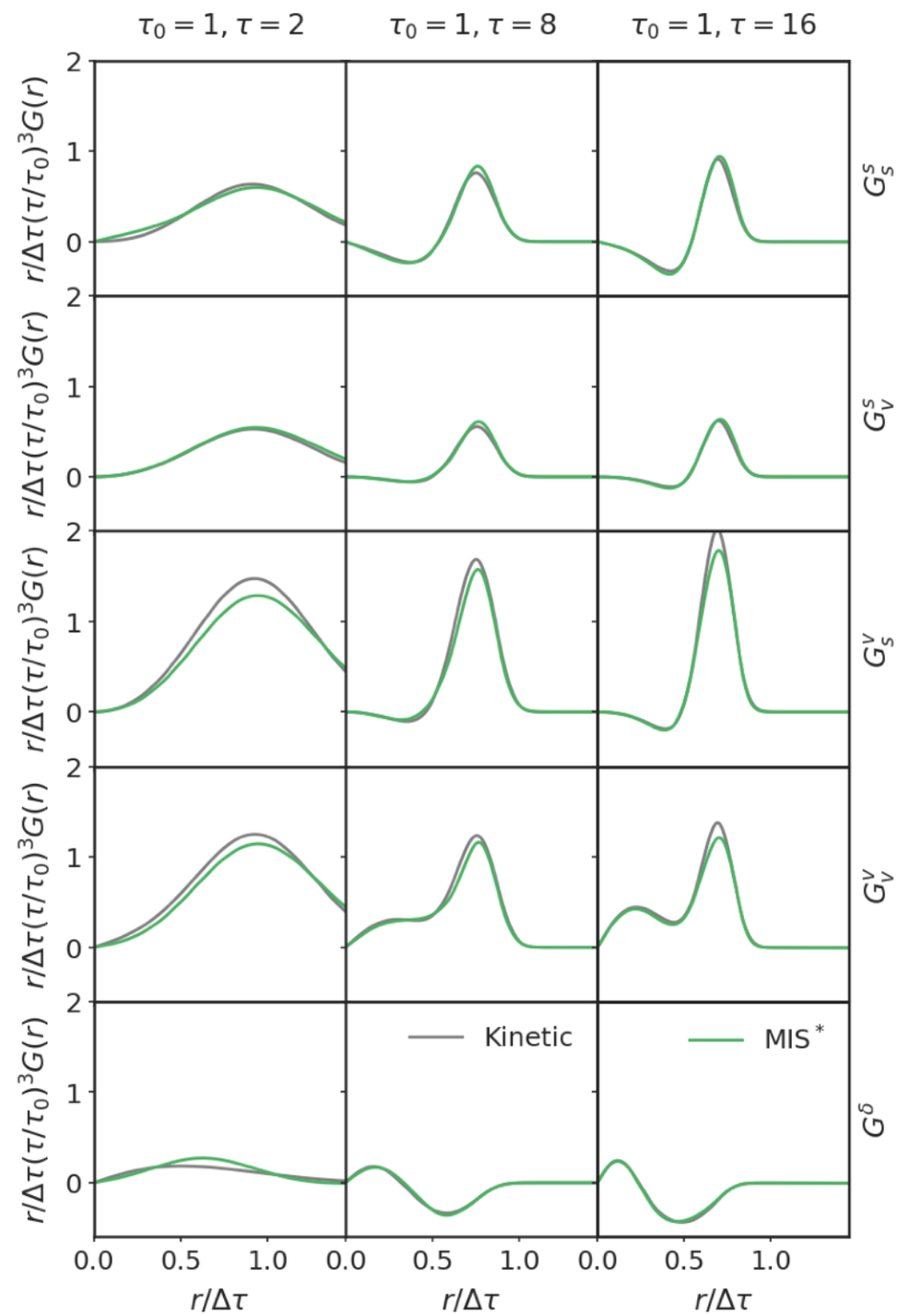


MIS* describes energy-momentum response (5 different response funs)

$(\delta, r) = (0.15, 0.7)$

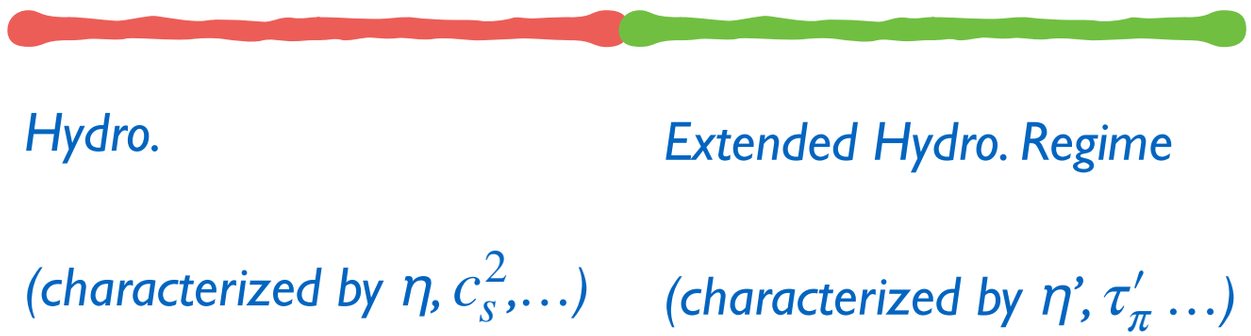


vs viscous hydro



vs MIS

Discussion



- The success of MIS* confirms that in extended hydro. regime (EHR), the characterization of QGP mesoscopy can be simplified.
- Responses in different microscopic theory can be described by the same effective models such as MIS*.
- Properties are characterized by a few parameters.

Summary and outlook

- We introduce extended hydro. regime (EHR) scenario for QGP-like system at intermediate scale and illustrate its generality.
  - Collective excitations dominate even at intermediate gradient.
  - The description at mesoscopic scale simplifies under EHR scenario.
- Observables: jet-medium interaction? small systems?
- Understanding the evolution of QCD at extreme density (HICs) may shed light on that at extreme virtuality (EICs).

Back-up

Shear channel

The domain of EHR is relatively narrow in shear channel for both kinetic theory/holography.